PXIE MEBT Bunching Cavity Design Proposal

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I. Introduction

Conceptual RF design of a cavity that can serve as a buncher in the PXIE MEBT section of PXIE was made early in 2012 and reported to the Project X collaboration meeting at LBNL [1]. At this stage, the design was configured to respond to the beam dynamics requirements by providing accelerating voltage of sufficient amplitude in the gap space defined by the velocity of charged particles (H^-). From several options that were analyzed, a quarter-wave coaxial resonator with the frequency of 162.5 MHz was chosen for implementation as this approach promised modest space occupied by the cavity in the beam line and moderate power loss. Possible steering effect and multipacting were studied at that point and found not to be a serious obstacle. It was also demonstrated by modeling that power couplers and tuners previously designed and built for HINS project can be successfully re-used in the buncher. As this design approach allowed meeting all requirements for the bunching device imposed by the beam dynamics study, it served as a basic reference point when the Functional Requirement Specifications (FRS) document [2] was issued.

In accordance with [3], after the FRS is approved, the next step of the cavity design sequence should be the release of Engineering Specification (ES), which must serve as the main guidance when the mechanical design is made. The ES must take into account the requirements of FRS, preliminary RF design, requirements for interfacing in the MEBT channel, means of existing and reliable techniques commonly used for RF cavity fabrication, and additional factors that can arise during preliminary stage of corresponding design study.

Two major questions of the cavity design remained after the conceptual RF design was suggested in [1]: details of how the cooling of the central stem could be effectively arranged, and how to make flange to flange size of the cavity in the MEBT beam line smaller to allow installation of additional diagnostics. Both issues were addressed during preliminary design study, the goal of which was to come out with a mechanical design concept and fabrication scenario that would results in building a cavity with RF properties close to those described in [1]. This note summarizes results of this study.

II. Mechanical Design

To simplify cavity fabrication, it was suggested (and found possible by corresponding RF modeling) to use the central stem with the round cross-section instead of elliptical one that was assumed in [1]. To ensure proper alignment of beam line elements and to save the longitudinal real estate occupied by the cavity, special shape of the central block of the cavity was proposed; corresponding RF modeling indicated no significant changes in the cavity RF properties. Main components of the BC assembly are shown in Fig. 1.

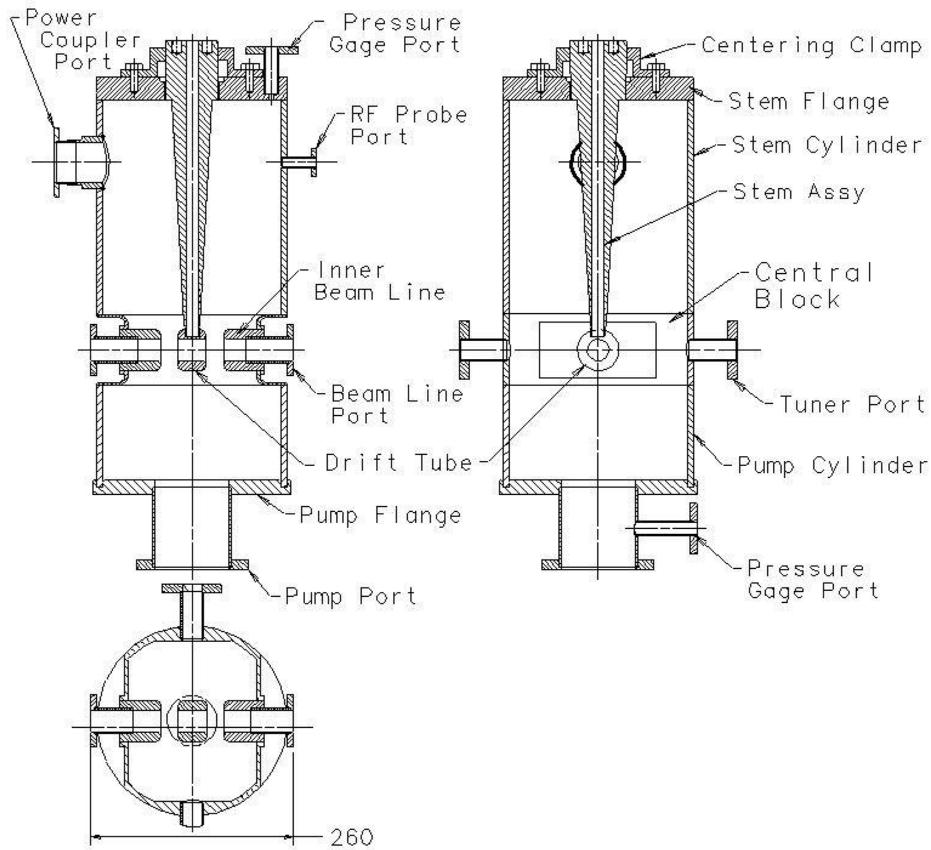


Fig. 1: Buncher cavity: main components and the naming agreement

The cavity consists of the next main subassemblies:

1. **Central Block** with two **Beam Line ports** and two **Tuner ports**.
2. **Stem Assembly** with the **Drift Tube** brazed in.
3. **Stem Cylinder** with ports for the **Power Coupler** and the **RF Probe**.
4. **Stem Flange** with a **Centering Clamp** for the **Stem** alignment during brazing and with a **Pressure Gage Port**.
5. **Pump Cylinder** with a **Pump Port** and a **Pressure Gage Port**.

These subassemblies are joined together by furnace brazing. As was suggested in [1], power coupler and tuners employed in the HINS RT (325 MHz) multi-spoke cavity, which have been built and tested, will be used with the assembled cavity. It is assumed that precision of RF modeling and accuracy of fabrication can ensure that the cavity frequency will fall within the range that can be handled by the tuners used as a part of the cavity final assembly. Geometry of the BC is detailed in Fig. 2. The main geometric feature of the model that defines the beam dynamics is the distance L_{dr} between the mid-planes of the two accelerating gaps of the cavity. This distance is fully defined by the speed of particles βc; for H^- ions coming out of the PXIE RFQ section with the kinetic energy of 2.1 MeV ($\beta = 0.0668$), $L_{dr} = \beta c/2f = 61.66$ mm.

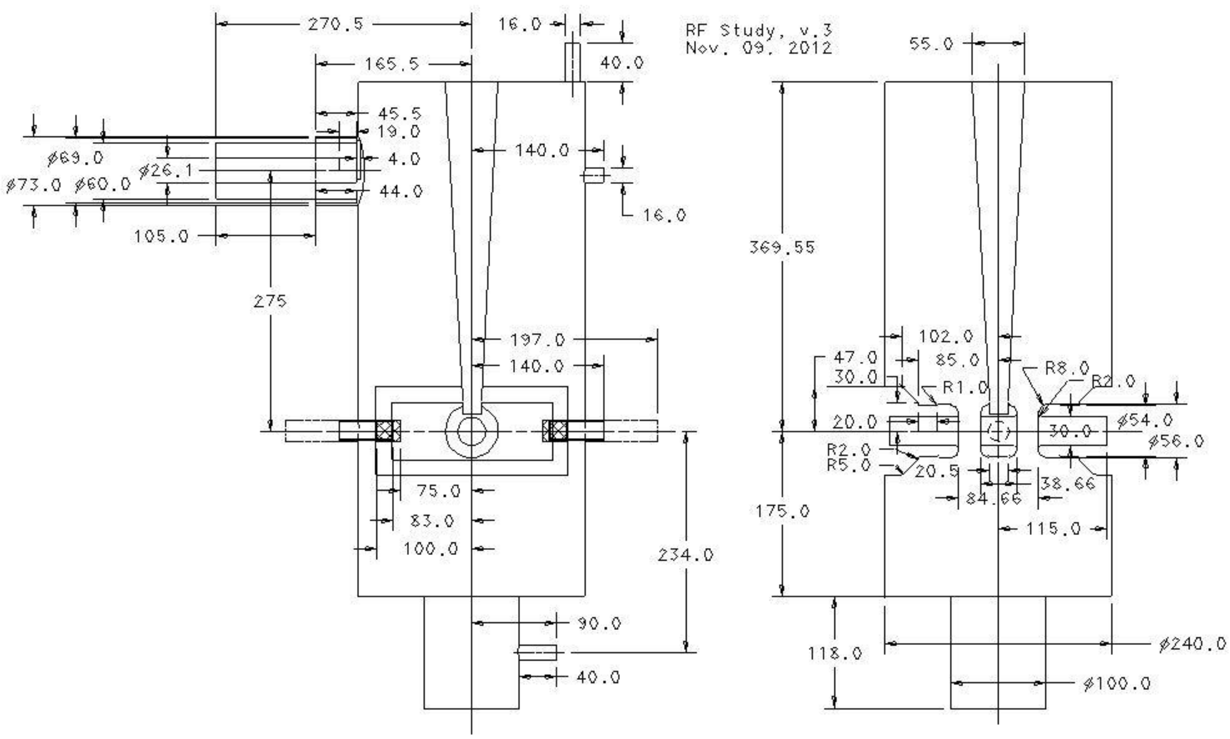


Fig. 2. RF model of the Bunching Cavity; $f|_{20°C}$ = 162.54 MHz.

The next geometric features of the model define the cavity frequency:

- radius of the cavity cylinder,
- length of the Central Stem and the Stem Cylinder,
- gap between the inner beam line elements,
- length of the drift tube.

Electric field on the drift tube must be taken into account while choosing the gaps in the beam transport section; shown in Fig. 2 configuration of the cavity has two 23-mm gaps (chosen as a result of analysis made in [1]), which results in the length of the drift tube of 38.66 mm. As the gaps mainly define the capacitance of the oscillator, the length of the stem and the inner diameter of the cavity define its inductance. The value of the inner diameter was chosen as a compromise between the overall size of the cavity and its shunt impedance (and hence power loss in walls of the cavity); the inner diameter of 240 mm was chosen in [1]. This choice mainly defines the length of the stem; as addition of each ports to the cavity changes its resonant frequency, corresponding changes in the stem (and the stem cylinder) length must be made to compensate for the change.

Following agreement is accepted in further description of the design: the base line for all vertical dimensions is the axis of the beam line; for the transverse dimensions, the base line is the vertical axis of the cavity.

III. Sensitivity of the frequency to critical features of the geometry

Sensitivity of the cavity frequency to the length of the Stem Cylinder in the geometry shown in Fig. 2 is **-350 kHz/mm.** The right choice of this length must take into account the temperature. As the nominal temperature of the cavity is 35ºC in accordance with the FRS, when low level RF measurement are made at room temperature (20ºC), the frequency must be higher. Having in mind the $1.66 \cdot 10^{-5}$ 1/K thermal expansion coefficient of copper, at 20ºC the cavity must be tuned to the frequency f_{20C} = 162.54 MHz.

Adding the power coupler port makes the resonant frequency 46.5 kHz lower; adding the central electrode and the loop changes the frequency drop by ~-7±3.5 kHz (the sign depends on the condition at the end of the port: +3.8 kHz for the case when metal plug is used to close the port and -3.5 kHz when a perfect magnetics boundary condition is used.)

Tuners used in the HINS accelerator front end will be installed in the BC. The diameter of the tuner rod is 20 mm, and the range of the movement of each of the tuners is 25 mm. Tuning diagram in Fig. 3 is shown for the case when the tuners' end position (that is the distance of the tuner end from the vertical axis of the cavity) is changing between 75 mm and 100 mm.

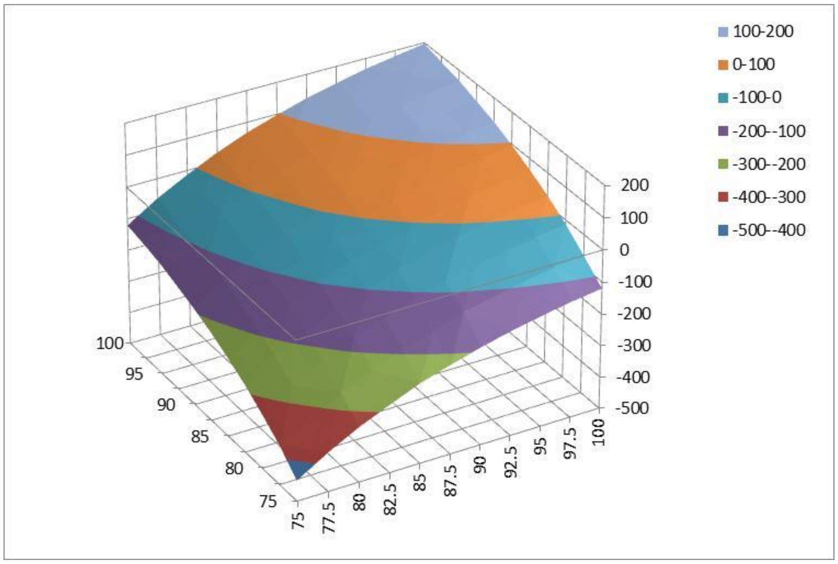
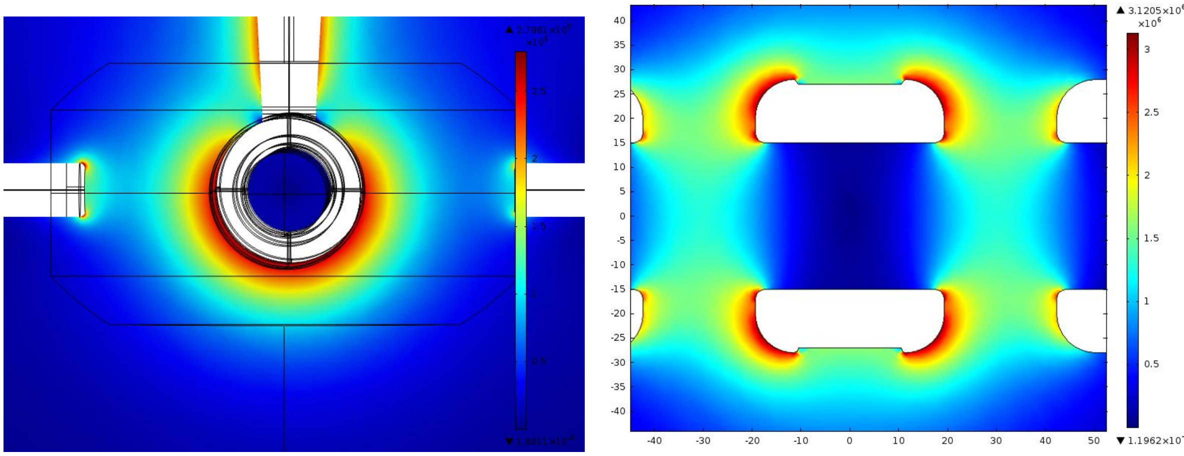


Fig. 3. Tuning diagram; zero frequency shift corresponds to the 87.5 mm tuner position.

The total range of the tuning by the two tuners is ~600 kHz with the most responsive part when the position of the tuner ends is closer to the vertical axis. To ensure close range of the frequency tuning in both directions from a nominal position, this position is shifted towards the axis (83 mm) from what is shown in Fig. 3.

The maximum electric field on the tuner in the position T = 75 mm for the maximum accelerating field integral of 80 kV is ~2 MV/m, which is well below the maximum field in on the surface of the drift tube (3.3 MV/m); this is illustrated by field maps in Fig. 4. At the 75 mm tuner position, the power dissipation in the tuner rod is evaluated to be less than 0.5 W.



a) b)

Fig. 4. Electric field map in the plane of the tuners (a) and the beam line (b)

As was already mentioned, important parameters of the cavity design are the gap between the ends of the inner parts of the beam line and the length of the drift tube. Graph in Fig. 5 shows sensitivity of the frequency to the distance between the ends of the inner beam line elements: it is **+430 kHz/mm**.

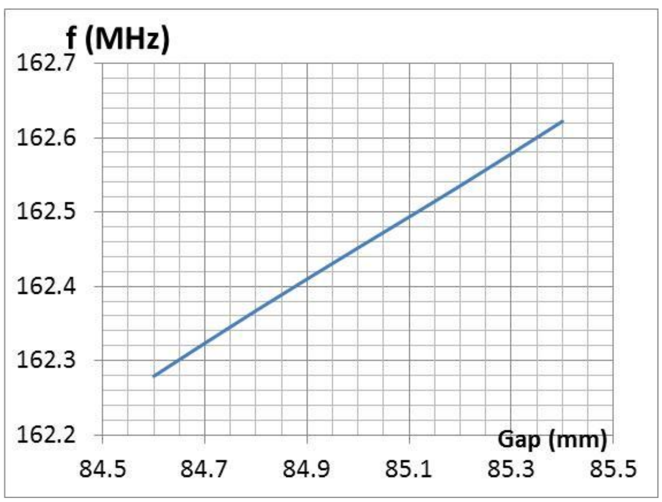


Fig. 5. Resonant frequency sensitivity to the length of the gap between the inner beam line elements; the length of the drift tube is 39 mm.

The frequency change in Fig. 5 is due to the changing capacitance between the beam line elements of the cavity and the drift tube attached to the central stem. Similar effect is taking place if the length of the drift tube is changing; corresponding curve is shown in Fig. 6. Sensitivity of the cavity frequency to this parameter is **-750 kHz/mm**.

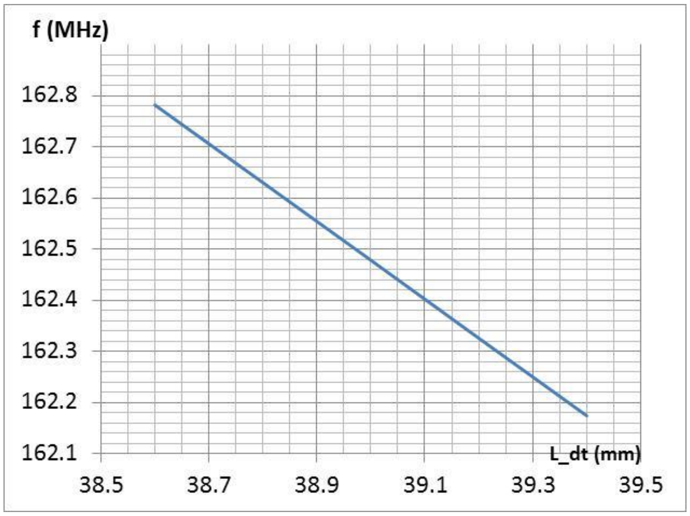


Fig. 6. Sensitivity of the frequency to the length of the drift tube; the distance between the ends of the beam line elements is 85 mm.

As the sensitivities of these two modes of the geometry distortion are quite different, we must recognize that even if the partial gaps (23 mm gaps in the present version of the RF design) do not change, the frequency can drift when both the drift tube length and the distance between the ends of the beam line elements change in phase. Graph in Fig. 7 shows the sensitivity to this mode of geometry distortion, which is **-333 kHz/mm**.

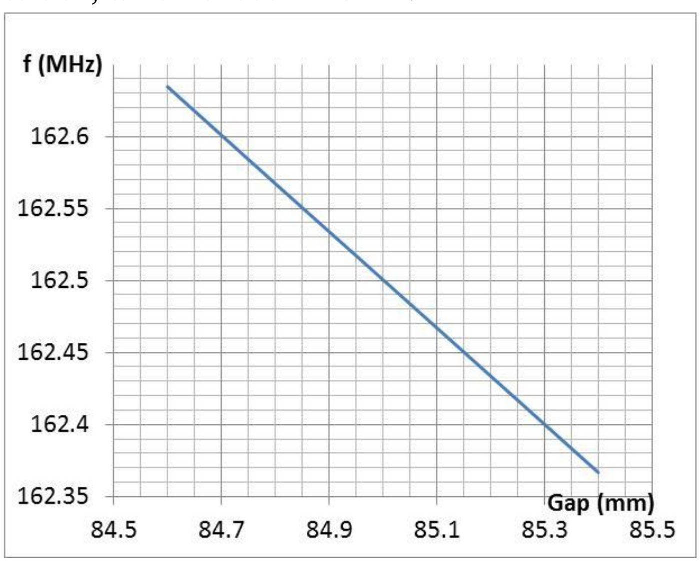


Fig. 7. Sensitivity to the combined geometry distortion with the constant partial gaps.

IV. Cavity Design and Assembly Options

Major components of the cavity that geometrically define RF properties (Fig. 1) must be made of C101 copper. All ports must be equipped with stainless steel CF-type flanges, which must be welded after the cavity is fully assembled and the working frequency is verified. This requirement is due to a possible softening of stainless steel flanges during the final brazing step at about 800°C.

While studying possible ways to build the cavity, a goal was set to use assembly procedures with minimum number of brazing steps. An additional, although not a defining, goal of this study was to attempt to make the flange-to-flange length of the cavity in the beam line as small as it is reasonably possible (the maximum acceptable length of 350 mm is stated in the FRS, but shorter axial size of the cavity is highly beneficial from the point of view of cavity integration into the beam line). The choice of the assembly process presented in this note was made based on the existing experience in the field and technological capabilities of one of potential vendors.

The analysis of the resonant frequency sensitivity to different modes of cavity shape change made earlier shows that the most critical part of the assembly is the central block. The nominal (reference) distance between the ends of the beam line elements is 84.66 mm. Having in mind the accuracy of assembly by brazing of ±0.25 mm, machining accuracy of ±0.05 mm, and the accuracy of measurements of ±0.025 mm or better, a way of compensating the assembly uncertainty can be proposed by making the gap size measurements after brazing in the beam line elements and making corresponding correction to the drift tube length. This way, a ±0.1 mm dimensioning uncertainty in the positioning of the elements in the central block can be reached with resulting frequency deviation of ±50 kHz, which can be compensated by engaging one of the tuners.

The number of possible brazing steps during assembly is limited due to the limited choice of brazing alloys. To ensure satisfactory mechanical properties of brazing connections, and to comply with the strict requirements by FRS on the residual pressure, only silver- and copper-based alloys can be used; list of acceptable brazing alloys can be found in the Attachment. The sequencing of brazing operations must take into account the need to lower brazing temperature in each successive brazing operation.

<u>Central Block</u>

The Central Block is one of the most critical parts of the cavity as the gap between the inner beam line elements must be executed with rather high precision. This section of the note proposes a way to assemble the central block by **brazing pre-fabricated inner beam line elements** into machined block body. Shown in Fig. 8 is an example of brazing arrangement. To make possible simultaneous brazing of two beam line elements (to reduce the number of brazing steps), main seams are oriented in the horizontal plane, and a ring-shaped brazing filler material with calculated weight is used. Special way to prepare mating surfaces can ensure required alignment accuracy and uniform filling of the brazing slots; example of this brazing prep is also shown in Fig. 8. High temperature alloys must be used for the brazing; e.g. Nioro (955 °C) can be used to braze stainless steel tube into the copper beam line element, and Silcoro 75 (895 °C) can be used to braze the beam line elements into the Central Block. Moderate vertical force must be used to get proper position of the elements after brazing and avoid deformation of the central block.

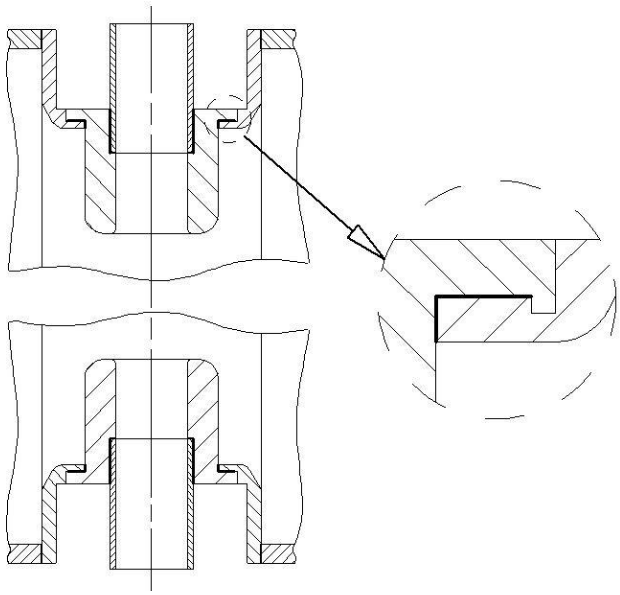


Fig. 8. Brazing the inner beam pipe elements into the Central Part.

Two tuner ports made of stainless steel can be brazed into the Central block using Silcoro 60 (845 °C) alloy.

Stem

The Stem is pre-assembled with the Drift Tube (both made of C-101) by furnace brazing using a high temperature gold-based alloy (e.g. Silcoro 75).

Stem Cylinder

The Stem Cylinder is assembled with the Power Couple port and a port for an RF probe (antenna).

Stainless steel pipe for the RF probe is directly brazed in the shell of the Stem Cylinder using Nioro (955 °C) alloy. Thick-wall copper cylinder with preliminary braised in stainless steel pipe (Nioro, 955 °C) can be braised to the wall of the Stem Cylinder (Silcoro 75, 895 °C) using a saddle feature machined on the copper part or a local reinforcing thickening of the cavity wall. Fig. 9 shows one of possible ways of making the brazing preparations by using locally thicker cavity wall. The increase in the wall thickness (in comparison to the prep that was made on the HINS RT cavity) is needed to provide better rigidity of the area as the coupler in the buncher cavity is positioned horizontally, not vertically, and significant bending moment can result in the sizable frequency shift and possible permanent cavity wall deformation. A possibility of using an additional support and/or stress relieve must also be considered.

For any brazing operation on the cavity body, brazing technique must ensure that brazing alloys reach the inner surface of the cavity to guarantee a reliable RF contact along the perimeter of the port.

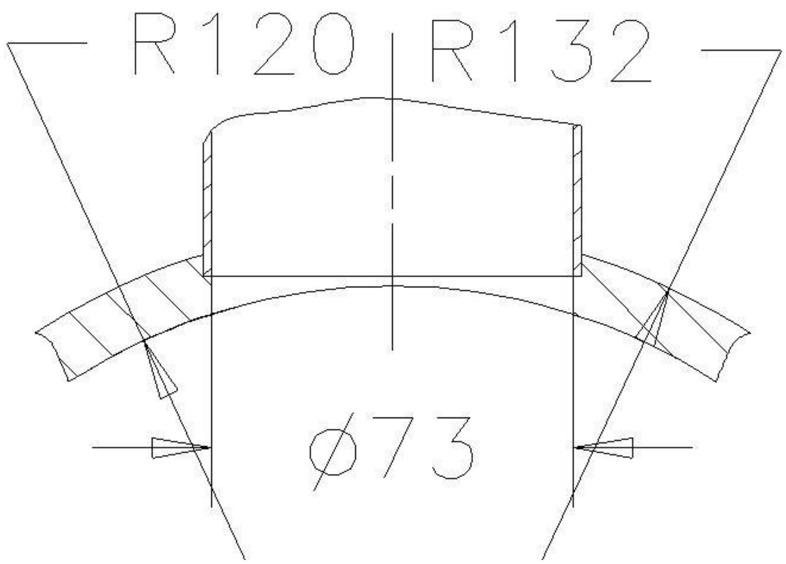


Fig. 9. Brazing in the coupler port.

Stem Flange

The Stem Flange is equipped with a Pressure Gage Port. Stainless steel pipe of the port is brazed into the flange using (e.g.) Nioro (955 °C) alloy. A Centering Clamp (Fig. 1) is installed on the flange to simplify alignment of the Stem assembly and to ensure reproducible re-placement during fabrication and assembly. After the Centering Clamp is attached to the Stem Flange, openings for the Stem in both parts are machined in a single setup. A gap between the Stem and the wall of the opening in the flange must be chosen to ensure uniform filling of the gap with alloy during final brazing step (Cusil, 780 °C) without any leaking of the alloy into the cavity.

Pump Flange

The Pump Flange is made of stainless steel and assembled with stainless steel Pump Port and with a Pressure Gage Port (also stainless steel) by welding. It is then assembled with the Pump Cylinder by brazing using Nioro (955 °C) alloy.

Final brazing operation

As all main sub-assemblies are fabricated, they must be connected by the final brazing operation using (Cusil, 780 °C) alloy. To ensure the required high accuracy of the assembly, quality RF surface, and to meet the high vacuum requirement, adequate brazing preps must be made. An example of a satisfactory arrangement for the brazing is shown in Fig. 10 below.

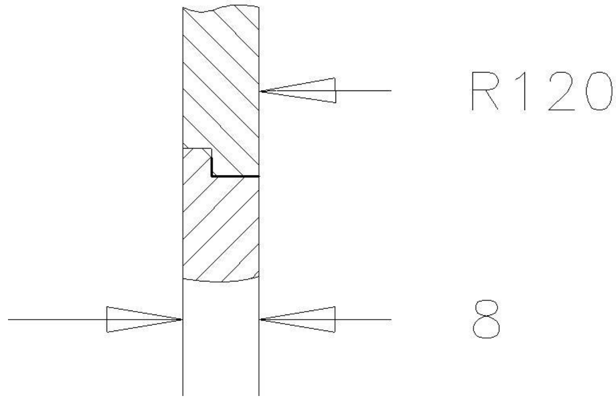


Fig. 10. Alignment scheme of the cavity parts during brazing

Here the matching surfaces are located outside the cavity and thus do not require any quality brazing. Instead they serve as alignment provision that allows reproducible reassembly of the cavity. They also ensure the possibility of having a uniform gap that needs to be filled with brazing material.

After the final brazing, all the parts of the cavity must be at their nominal position; proper tooling must be used at this stage to position the Stem assembly both vertically and horizontally. One of possible ways to make this alignment is to use a cradle-like support fixture (Fig. 11) to fix the Stem during assembly. This support cradle is removed after the vertical position and angular orientation of the Stem is verified and the Stem is fixed using the Centering Clamp (see Fig. 1). As the Stem alignment precision is critical for the cavity performance, this part of the assembly process must be well documented and corresponding quality control step must be defined. A different approach for the alignment can be considered and chosen by a vendor provided it satisfies the requirements of the assembly precision.

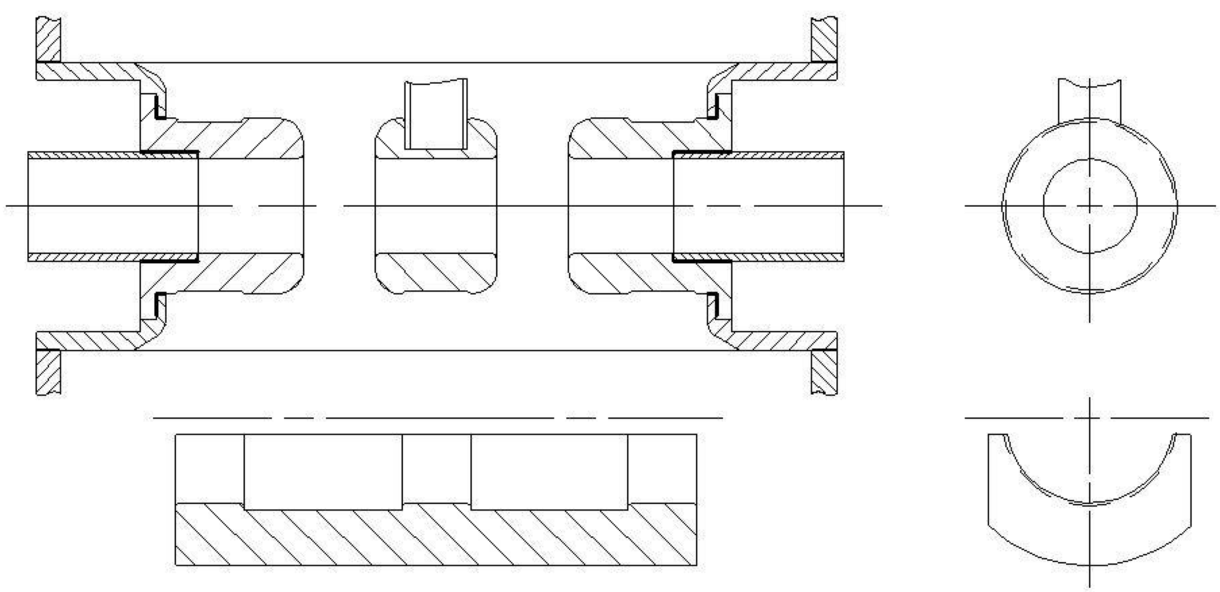


Fig. 11. Stem alignment fixture

Intermediate QC

Before the final brazing takes place, quality control procedure must be implemented to verify the quality of the sub-assemblies, including surface inspection, verification of major dimensions, and the cavity frequency. For the frequency check, the cavity must be assembled as it should be for the brazing. Any significant inconsistencies of the frequency measurement must be addressed and appropriate measures must be taken to bring it within a desired range.

During this QC session, temperature records must be made, and the measured frequency must be adjusted to the working temperature prescribed by the FRS (35 ºC).

To ensure write (theoretical) position of the Drift Tube inside the Central Part, the cavity is pre-assembled using an alignment fixture (e.g. like it was discussed earlier). The position of the Stem Assembly is then fixed using the centering clamp (or equivalent feature located outside the cavity), and the alignment fixture is removed. Mechanical measurements can be made then and the frequency of the cavity can be measured. This operation must be repeated several times to understand reproducibility of the assembly.

Assembly Procedure

The next cavity assembly process can be proposed:

1. Assemble the Central Block and measure the distance between the ends of the beam pipe.
2. Make correction to the length of the drift tube to compensate for possible (evaluated) deviation from the nominal resonant frequency.
3. Assemble the Stem.
4. Pre-assemble the cavity and measure the resonant frequency before the final brazing.
5. Evaluate means of possible frequency corrections if needed.
6. Make the final brazing.
7. Make the final (acceptance) frequency measurements without and with installed tuners and power coupler.

V. Cooling the cavity

Total power loss in the cavity walls at 80 kV of the combined gap voltage is ~700 W with ~500 W dissipated in the central stem. As a traditional cooling approach can be used for cooling the body of the cavity, to remove the power deposited in the central stem, a different cooling scheme was needed so that the temperature of the stem do not rise too high. After several way of making cooling channels were studied and the main concern of the channel blockage by lime deposits was identified, a coaxial counter-flow cooling scheme was proposed. In this scheme, the cooling circuit was configured so that it could be easily disassembled for cleaning or replacement of the cooling insert. An example of implementation of this approach is shown in Fig. 12.

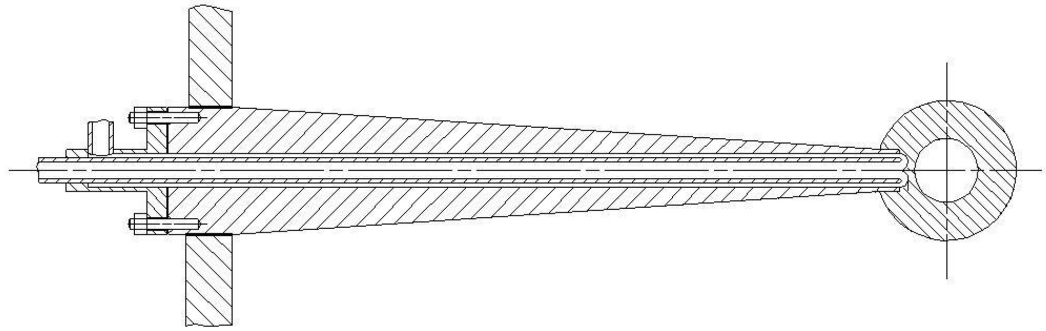


Fig. 12. Concept of a counter-flow cooling scheme.

Cooling effectiveness was another issue to investigate. Reference [4] describes a test that has been conducted to verify this approach to the cooling and to compare the measurement results with that of corresponding modeling. Fig. 13 shows the layout of a mockup used for the testing.

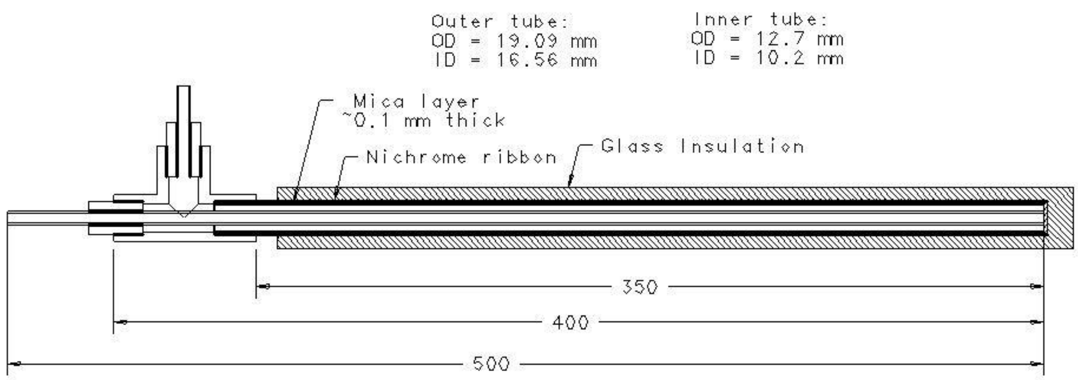


Fig. 13. Mockup of the central stem cooling circuit.

The power as high as 1 kW could be easily handles by the circuit (Fig. 14).

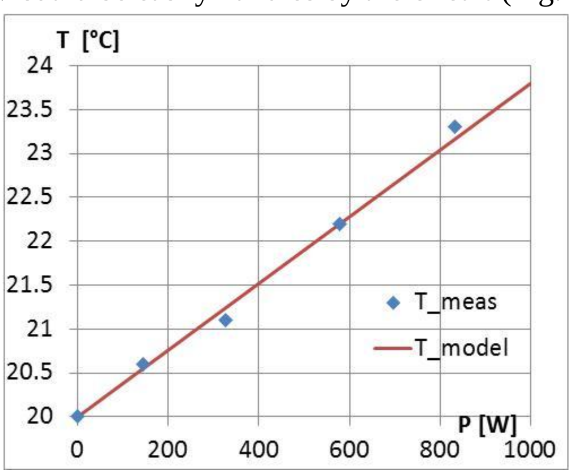


Fig. 14. Cooling water temperature increase as a function of the heating power

VI. Installation of the cavity in the MEBT channel

The cavity must be installed in the beam line of the PXIE MEBT section. The FRS specifies the installation accuracy of 0.5 mm RMS for linear displacement and 3 mrad RMS for pitch and yaw, so the cavity must be firmly attached to an alignment fixture on the section's framework. As this accuracy is well within existing experience, details of needed arrangement can be worked out later, when the frame design is made, but one of attractive solutions would be to introduce a base plate attached to the Central Block or to the Pump Cylinder as it is shown in Fig. 15.

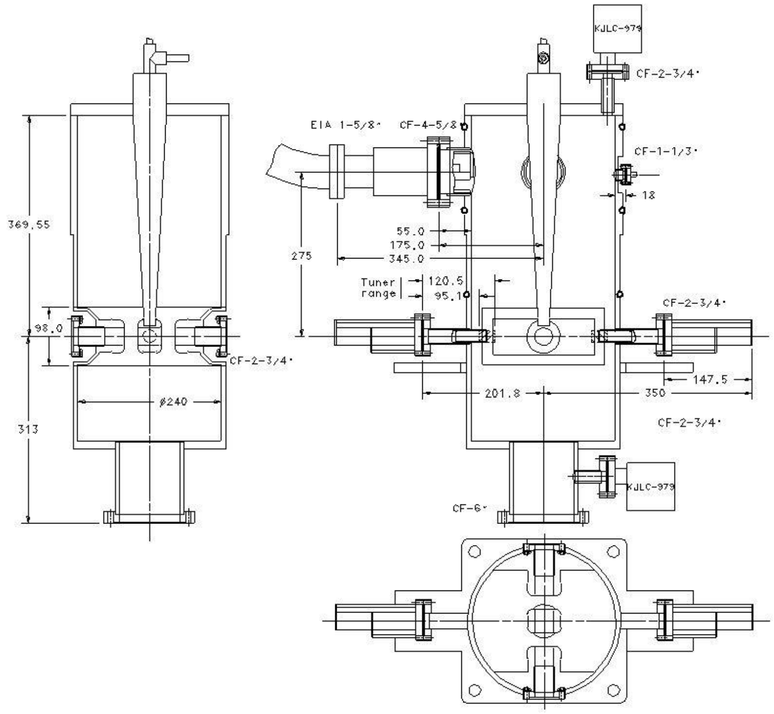


Fig. 15. Layout of assembled bunching cavity.

Artistic view of the cavity is shown in Fig. 16.

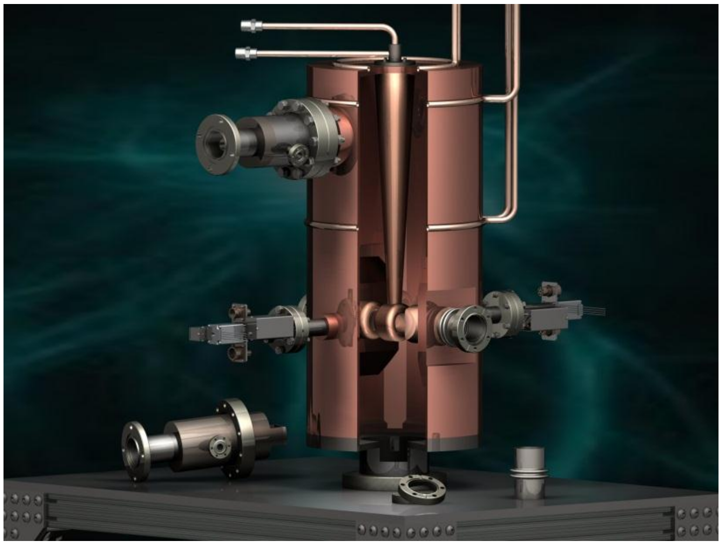


Fig. 16. Bunching Cavity.

Acknowledgements

Design approach presented in this note evolved as a result of multiple discussions at different levels within Technical Division. Authors gladly express their gratitude to T. Arkan, E. Borissov, A. Makarov, and L. Ristori for their attention and suggestions they made to help us to deal with the issues we met at this stage of the design.

References:

1. G. Romanov, et al, “MEBT Buncher Cavities”, April 2012 Project X Collaboration meeting, PX database, doc. 1024-v1, Apr. 10, 2012.
2. Bunching Cavity for PXIE MEBT. Functional Requirements Specification. PX document #1071-v1. FNAL, July 16, 2012.
3. FNAL Engineering Manual, http://www.fnal.gov/directorate/documents/FNAL_Engineering_Manual.pdf
4. I. Terechkine, T. Wokas, “Testing Central Stem Cooling Concept of the PXIE MEBT Bunching Cavity”, FNAL TD note TD-12-015.

Attachment

Choice of brazing material

As the residual pressure requirement for the cavity is ~10^{-8} Torr, and required quality factor is ~10000, only oxygen-free high conductivity copper can be used to make the cavity; welding and/or brazing using gold-based and silver-based alloys can only be considered to assemble it. Tables below list brazing alloys available on the market to make copper-to-copper and copper-to-stainless steel assemblies. Melting temperatures in these tables can be compared with the melting temperatures of base materials: Ag - 960 °C, Au - 1064 °C, Cu - 1083 °C.

Table 1. Alloys for brazing copper to copper

Name	**Ag**	**Au**	**Cu**	Temp. range (°C)
Cusil	72	0	28	780
Silcoro-60	20	60	20	845 – 835 (10)
Silcoro-75	5	75	20	895 – 885 (10)
80Au-20Cu		80	20	910 – 908 (02)
Silver	99.99			960
50Au-50Cu		50	50	970 – 955 (15)
40Au-60Cu		40	60	1000 – 980 (20)
35Au-65Cu		35	65	1010 – 990 (20)

Table 2. Alloys for brazing copper to stainless steel

Name	**Ag**	**Au**	**Cu**	Ni	Mn	Temp. range (°C)
Copper - ABA						1024 – 958
Cusil – ABA						815 - 780
Silcoro (60, 75)						(845 – 835), (895 – 885)
Nicuman-37			52.5	9.5	38	925 - 880
Nioro		82		18		955

As Cusil is eutectic material with the lowest melting temperature and zero softening range, it will be used for the final brazing. High temperature Nioro alloy, which is also eutectic material will be used for brazing stainless steel tubing into copper body of the cavity during preliminary stages of the assembly. Important requirement for the brazing operation is that brazing alloy must reach the inner surface of the cavity, so that RF surface currents are not interrupted.

Available forms of the mentioned alloys are foil, flexibraze, wire, powder, extrudable paste and preforms. More information about Brazing filler materials can be found at the web site of WESCO Metals: http://www.wesgometals.com/